TRANSITIONING AERO GAS TURBINE SEALING TECHNOLOGY TO POWER GENERATION INDUSTRIAL GAS TURBINES

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When I first started coming to the NASA seals workshops, I was working on gas turbine engines that you could fit in your briefcase—now I am working on ones you could walk through with the rotor out. There are many companies and people involved in the work I wish to discuss, i.e., Cross, EGG, Stein, other seal companies, and technology partner companies—in addition to DOE which is sponsoring much of the work.

I would like to start by showing view graphs of large industrial gas turbines and power plant installations. This power plant is at Fort Lauderdale, Florida with four gas turbines enclosed inside this structure. Those are stacks coming out at the top. Each CT (combustion turbine) unit has a steam turbine with a boiler in-between. I am trying to give you a perspective because in earlier talk today we learned about how large engines could get in the utility business. Here's our 501 D5 engine—the man beside the engine appears to be very small and here is an engine on a railroad car which is how we ship them in US. All parts are not on these engines yet or you could not ship the unit. Here shows you three engines at different stages of assembly. It's a unique experience to see how quickly they are put together and how the parts are aligned. Tight tolerances must be maintained in order to align seals. This is done different ways including laser alignment. These are large engines but they do scale, at least approximately, so what we did with Teledyne's small engines applies here.

A plug for Westinghouse—this is their product line with the 501F engines that you saw at Fort Lauderdale, the 501G is the next generation engine, and the 501 ATS is our current state of the art ATS engine (comparable to what GE calls their "H"). This chart shows that the required efficiency for the ATS must exceed 60%. It is being accomplished for 60 cycle applications and with an attendant increase in power over current engines. Also, there is also a whole series of CT's, we call the 701 series which is the 50 cycle product line and they are even larger in size. Besides efficiency another requirement for new CT's is a low NOx level. The x axis in this plot is year of engine introduction. You can see NOx decreasing to lower levels with year. Also, the engines have to be fuel flexible, natural gas or liquid fuel plus future conversion to coal gas and biomass gas. Note that the charts show for NOx are based on natural gas. As taxpayer you want high efficiency and low NOx, but no utility will buy your machine unless one gets the cost down and maintainability, reliability and availability are held.

We have chosen to call the Westinghouse ATS engine, the "501ATS" and here is a schematic of it. This chart is hot off the press. The engine has a four stage turbine, a high pressure ratio compressor, and low NOx combustors. Relative to the engine seals and secondary flows, we have closed loop coolant which is either steam or air. Closed loop air is air taken from the combustion shell and eventually returned to the combustion shell after providing cooling. Closed loop cooling contributes significantly to the engine reaching the ATS efficiency levels. This was the chart shown earlier depicting some of the engine characteristics including the four stage turbine which are standard for most of the Westinghouse engines.

The design approach for new engines is to adapt proven successful technologies and features from our product line and incorporate aero-derivative and advanced technologies, materials and coatings where possible. Westinghouse has not been in the aircraft engine business for many years so we rely on our partner companies and vendors for aero derivative technologies.

I would like to point out that the vendor technology we are transitioning was funded originally, at least in part, by NASA and the Air Force, i.e., good synergism with the DOE funded ATS program. Further transitioning occurs from our partners whose expertise and resources were developed for aero engines. They provided consulting or engine design, risk analysis, lower cost manufacturing, design codes, and component rig testing. Consequently, we are better equipped to develop the best product to meet design requirements.

Comparing design of aero gas turbines with large industrial ones is interesting. In aero engines we are told that you pay a price when you scale down to small sizes. But it turns out that you also pay a price when you scale up to large sizes—no win situation. In theory you should be able to gain by scaling up in size, but very large castings drive costs up. Industrial engines run primarily at constant speed - great because you don't have a pilot continually moving the throttle or late flights going as fast as they can to make up time. Industrial engines are designed for one speed but getting the engine up and down from that speed presents design challenges. Also, there is another major issue - long operating life. In the ATS program the life cycle costs are based on about 150,000 operation hours with 24,000 to 48,000 hours between partial tear downs.. An advantage for the ATS engine is starting from a clean sheet; whereas in retrofit engines you are highly constrained by the current design.

An advantage for sealing improvements in industrial engines is that the leakage reduction goals are modest. In some cases only moderate reductions are allowed as you still have to purge downstream cavities. Another constraint for sealing hardware is that is must be segmented because of the horizontal split line and a general arrangement so you can take off the top half to repair the engine. We would like to have a minimum changes or treatment of hardware to accommodate improved sealing. For example, we will not put coatings on the rotors surfaces which brush seals run against. At Teledyne with expendable engines, you didn't want to put coatings on the rotor surfaces because of costs. Brush seals ran as well against uncoated rotors as coated ones. For industrial engines, the affected rotor parts are massive, so surface cracks etc. are not an issue in maintaining long hardware life and no coating is required.. Seal hardware has to be durable for hand field installation operation. If you've ever been to a site where overhaul is in progress - don't get in anybody's way - They are very tough men and women who do their business - There is a Westinghouse straw-boss that has a schedule and if behind he/she is pushing the workers to accelerate the work. It's not acceptable to say you've got to put this brush seal in very gingerly - they will say forget the brush seal we are going without it. Thus, you have to design seals so they can take the installation environment in the field. Also the start up cycle can be severe for seals for these engines. When you start up an engine, the rotor centrifugal growth occurs first so the seal closes together. This closure is significant because of the large rotor sizes. The gaps open up when the stationary part thermals take over and these parts pull away. Hours later the large rotor reaches thermal steady-state to form the final seal gap. The closure challenge is the difference between of the steady-state gap and maximum closure during start up. That difference will cause wear in the brush seal bristles. After many hours of operations the brush seals wear line to line at the maximum closure point so that you then have a effective single knife labyrinth seal, with that clearance

Sealing at static locations is also being improved for the ATS engine. It's very important to get any joints sealed where cooling air or steam may leak. For example, between large outer engine parts Stein seals are a standard bill of materials for our engines. A specific static location being considered for improved sealing at the combustion transition mouth in front of 1st vane. The transition duct between the combustor and first stage nozzle has to be cooled, via. closed loop with steam or air. This chart shows you a current combustor liner and transition mouth to give you some idea o f the hardware - those transition liners stand about this high off the floor and they have knife seals between them that grow together when the parts heat up. The top piece is very thick and rugged materials for the hostile environment and installation requirements at that location We have to improve sealing at these locations, as is was mentioned in the previous presentation, to minimize the difference between the combustor gas temperature and the rotor inlet temperature in order to keep NOx levels down.

This charts shows the different types of the dynamic seals being considered. The first is the common labyrinth seal. At Westinghouse the seals are formed with staggered teeth to get an effective step seal. The compliant seal is something that EGG is developing and we are looking to use it in various places in our engines. We are developing a face seal for the rear of the ATS rotor. We are bringing cooling air in the center of the shaft and or steam for closed loop. We use this type of seal because it has very low leakage. The problem with the face seals is scaling up in size. A face seal is OK at this location because the smaller size here. Another development area we are working on is transitioning turbine abradable tip seals for both stationary and rotating parts from aero engine development.

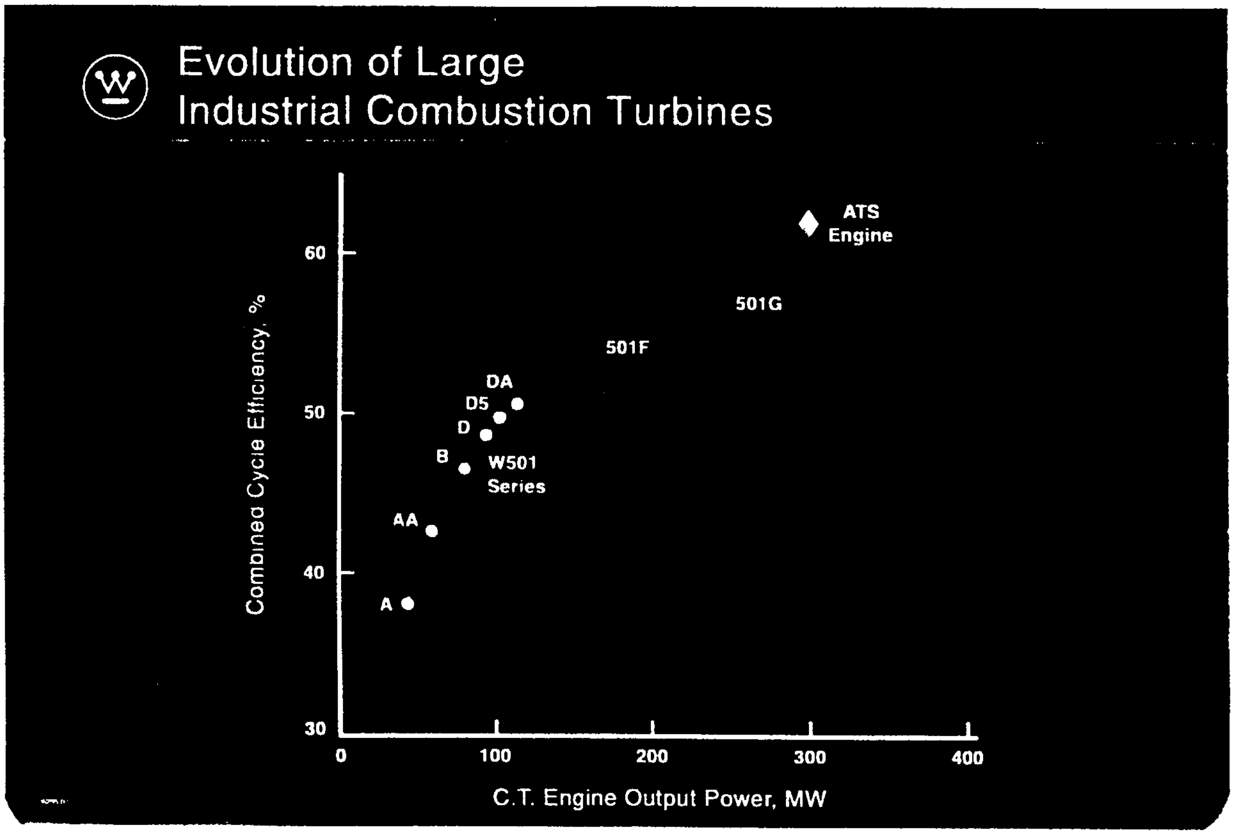
I want to talk briefly about brush seals. I have already given presentations in two AIAA papers. We initially worked with Cross Mfg. to find out if we can run against uncoated surfaces. That was successful so we begin to work with EG & G because their efforts with the Air Force and their manufacturing capabilities. We are focusing on one location of the engine at a time. To give you an idea of what brush seals look like for a large utility industrial engine, this is a complete seal ring and this is a segment. I have a segment sample you can look at after this presentation. In the program with EGG, we developing brush seals for many locations, using some of their technology and patented features to provide improved sealing with large closure cycles and pressure drops.

In summary, decreasing leakage in industrial gas turbines has significant payoff in performance. I hope I've demonstrated here that large utility gas turbines have different sealing constraints and requirements than aero engines. There are some overlaps so they are not a completely different set. And as I have listened to some of the talks this morning - some of these the unique features in industrial gas turbines are going to be appearing in aero engine requirements as they become larger - so maybe the aero derivatives can pay the aero engines back with technologies flowing in the reverse direction.

Questions

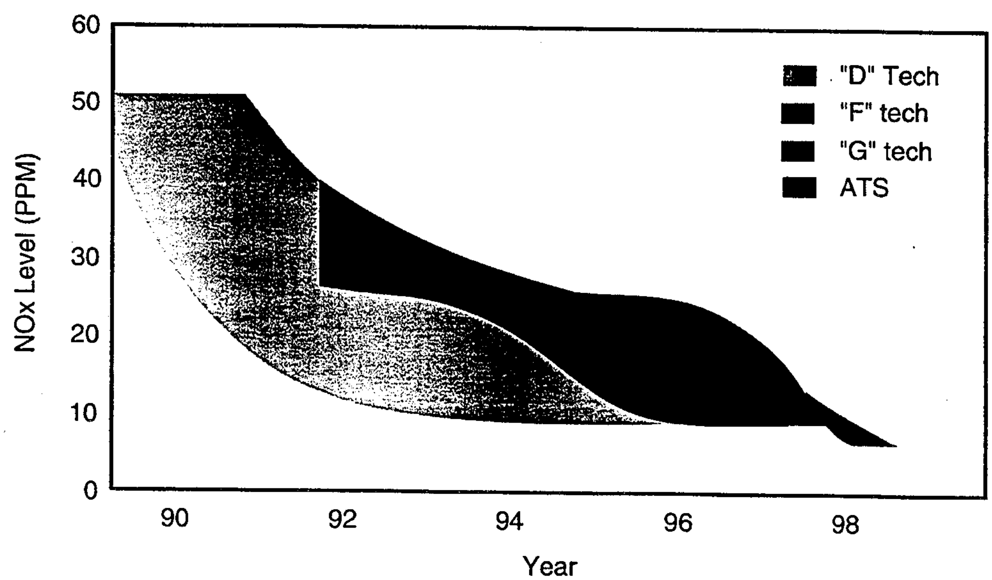
Q You said you do the design for a 150,000 hours but you could go for lower life?
A. 150,000 hours is for life-cycle cost analysis. We had to say how much the engine would cost to get to 150,000 hours. 24,000 hours would be a reasonable minimum for a given set of hardware. Minimum life varies with the part depending on how they are built and where they are located. For example, some of the combustor transitions go for only 8000 hours. However, we don't want to replace brush seals that often. Transition liners can be pull it out by someone crawling down in the engine - that's something you can get to once a year--like every 8000 hours. But for brush seal replacement, one would have to be take the top part of the engine off and that would be too expensive to do every 8,000 hours.

Q. In your brush seals do you ever get your leakage so low that you that you have a problem with your brushes getting too hot, or to put in another way, do you rely on some leakage to keep the bristles cool?
A. Yes, one does rely on leakage flow for cooling. Based on all the rig testing that I have seen, you get significant leakage reduction over a labyrinth seal but it's not as low as for example as a face seal which has an order of magnitude less leakage. In the bristle pack, you get both axial and circumferential flow that provides cooling. If the bristle stiffness is right, heating will not be excessive for the closure cycle to be encountered.



Over the last few years, large combustion turbines have evolved via. integrating advanced technology into their design. Overall plant efficiencies have increased from under 40% to over 60%, the latter in the ATS engine currently being developed. These new engines will significantly decrease the demand for our fuel resources. At the same time, the combustion systems of these engines have been improved so that emissions have been significantly reduced.

Low Nox Development

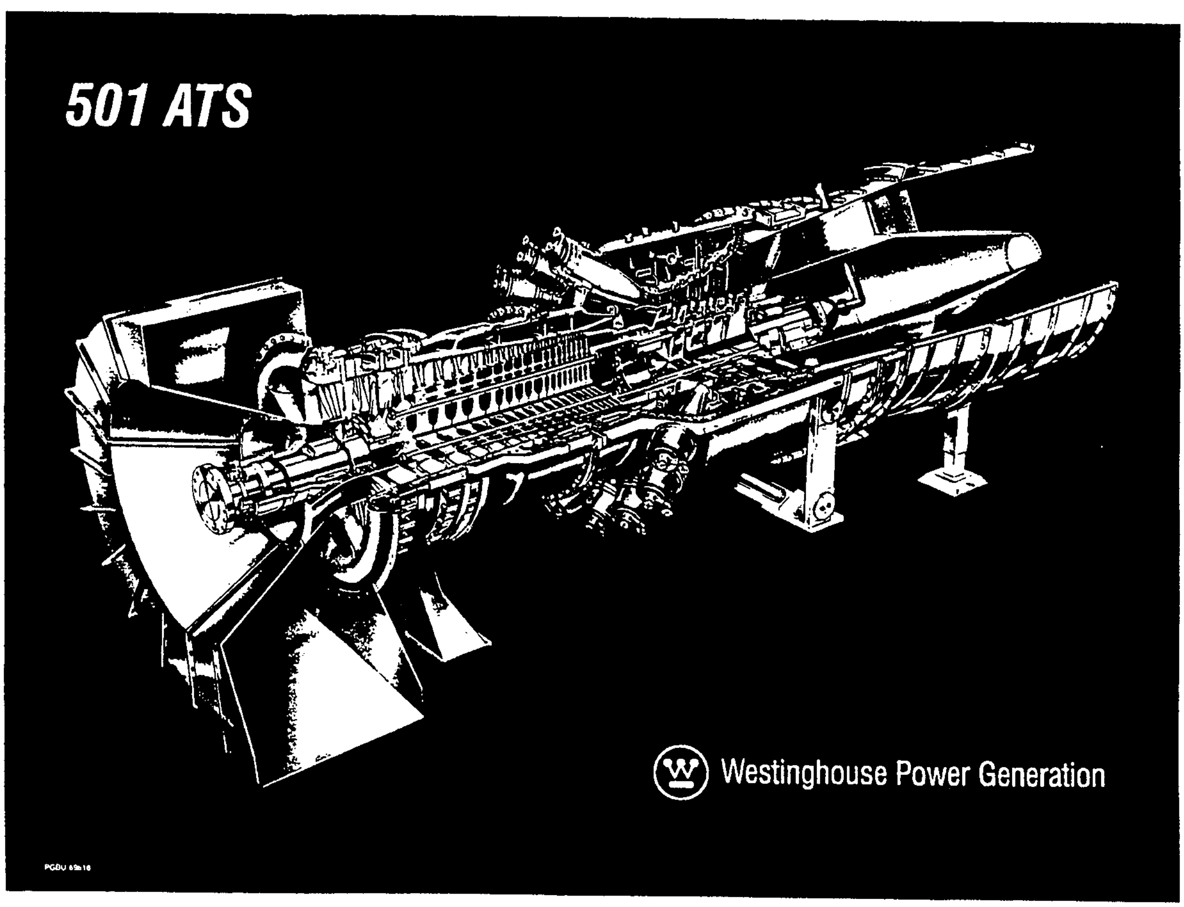


Advanced Turbine Systems (ATS) Program

- Greater than 60% net plant thermal efficiency
- Less than 10 PPM NOx emissions
- Reduce cost of electricity generation by at least 10%
- Fuel-flexible design operating on natural gas with provisions for future conversion to coal or biomass fuels
- Reliability - availability - maintainability equivalent to modern advanced power generation systems
- Commercialization in the year 2000

DOE's ATS program is a major driving force in the U.S. to improve industrial power plants. ATS objectives address efficiency, emissions, cost of electricity, fuels, RAM, and date of introduction. They force the development to meet the major needs of the power generation industry.

The Westinghouse 501ATS combustion turbine is a derivative of current engines with improved features incorporated. It is a major contributor to improving the overall ATS power plant.



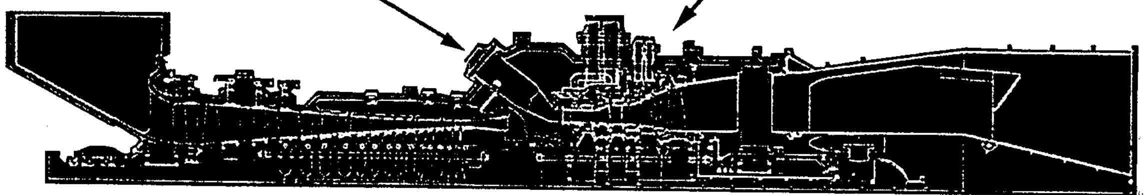
Advanced Turbine Systems

Combustion System

- Can-Annular Ultra-Low Emission Combustor
- 2700°F Class Burner Outlet Temperature
- Steam Cooled Combustors/Transitions

Turbine

- 4 Stage Advanced 3-D Design
- Closed-Loop Cooling
- Enhanced Sealing
- Aeroderivative Proven Materials/Coatings



Compressor

- Advanced 3-D Design
- Enhanced Sealing

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Advanced features in Westinghouse's ATS combustion turbine include: the compressor with advanced CFD design techniques; the combustion system with a higher firing temperature, but lower emissions; and the turbine with CFD aero design techniques, closed-loop cooling, advanced sealing, and improved materials.

The ATS engine design has aero engine technology integrated into current engines with proven performance, reliability, etc. Some of this technology was funded by the US government agencies. Alliance partner technologies are also used extensively. The design process includes reviews and testing to ensure fabrication, installation, and operation requirements will be met.

ATS Engine Design Approach

- Evolutionary design based on 501F engine
- Transitioning aero engine technology
  - From Alliance partners
  - From vendors, technology developed with government support, e.g., brush seals (USAF/NASA), ceramic abradable coatings (NASA)
  - Further development of technology, e.g., brush seals
- Integrating ATS funded technology development programs
- Reliability and maintainability analysis
- Risk analysis
- Manufacturing and cost analyses
- Design reviews (with internal and partner experts)
- Component and rig tests
- Fully instrumented prototype engine test
- Design issues/root cause analysis process

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ATS Engine Sealing Improvements

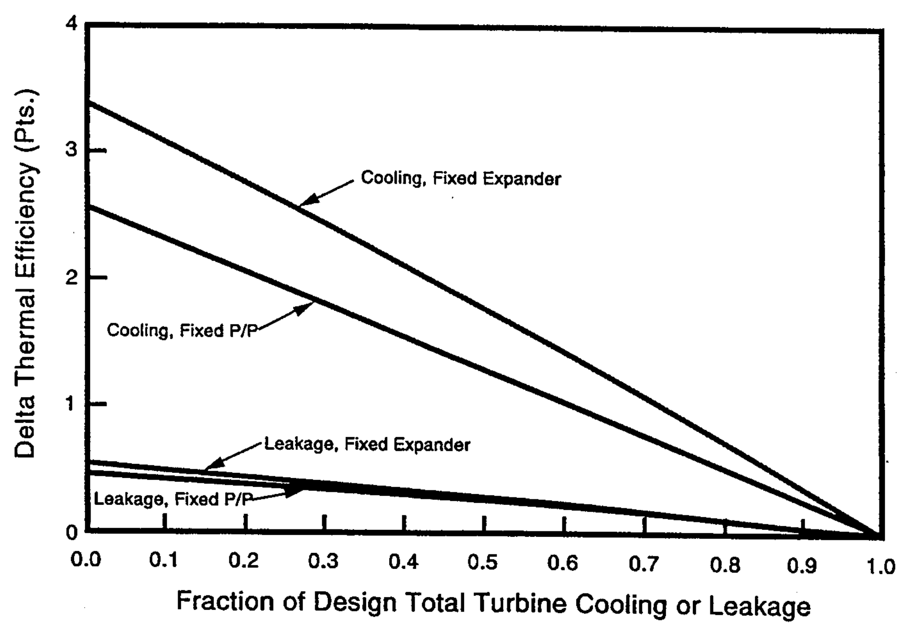
Contributes to:

- Decreased plant heat rate (improved cycle efficiency)
- Lower NOx emissions (via. improved static sealing at combustor transition mouth and in front of 1st rotor stage)

Improved sealing is an important part of evolving Westinghouse's ATS engine from current ones. The primary effect is to improve plant efficiency, but lower emissions is also a beneficiary.

Studies show that decreasing turbine leakage can impact the plant efficiency by as must as one-half of a percentage point. This seemingly small improvement is worth one to two orders of magnitude more in fuel cost savings and plant power output benefit than the increased costs of the sealing components.

Turbine Cooling/Leakage Effect on ATS Combined Cycle Efficiency



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Transitioning / Developing Improved Sealing

Motivation

- Improved sealing approaches developed for aero engines
- Large size engines - leakage may not scale up with size
- Engines run primarily at constant speed
- Fewer transient closure cycles than aero engines

There are several opportunities/advantages in transitioning and developing improved sealing for large combustion turbines. These include: availability of advanced aero engine sealing technology, large size of combustion turbines, and primary operation at a fixed condition.

However, there are also challenges associated with applying improved sealing in these engines. These challenges include: long required operating lives, large start-up cycle relative movements, handling durability, etc.

Transitioning / Developing Improved Sealing

Challenges / Requirements

- Long operating life
- Large radial and axial movements during start-up / shut down
- Operate within available geometry envelope and range of environment conditions
- Moderate to aggressive leakage goals
- Segmented because of horizontal split line
- Minimum treatment of adjacent parts (e.g., coatings for brush seal runners) because of manufacturing complications / costs
- Durable for handling, field installation and operation

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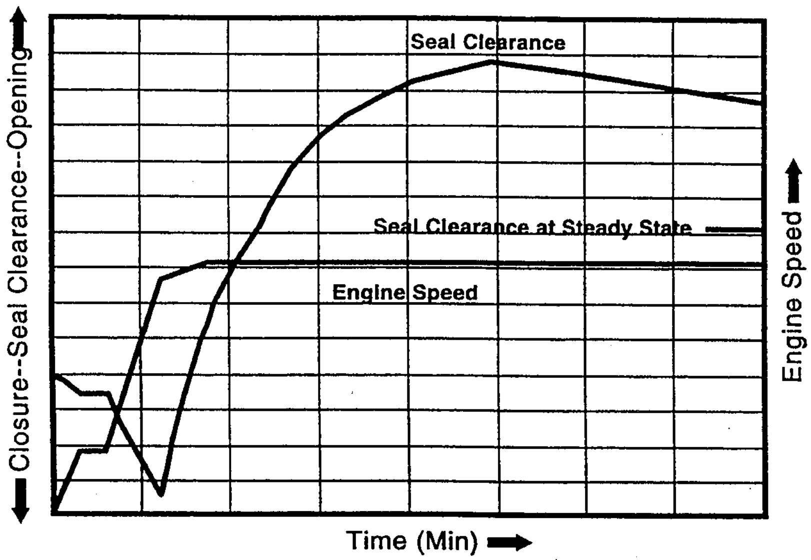
Start-Up Cycle for Turbine Interstage Location



- Closure mechanisms
- Pressure, temperature also changing
- Whirl closures not shown

One of the major challenges in improving dynamic sealing in combustion turbines is the large radial closures during start up. As the engine starts rotating, the gap between rotating and stationary parts immediately starts closing up due to centrifugal growth of the rotating parts. Then, the temperature of stationary parts starts increasing to open up the gaps. Eventually, the rotating parts heat up and closes the gap down to a steady-stage clearance. Unfortunately, the steady-stage clearance is greater than the minimum value during start up, and causes significant seal clearances at steady state. Clearances are also increased due to: orbiting of rotating parts as the rotor passes through critical speeds in starting up, and circumferential gap variations caused by the engine's split casing.

Sealing in combustion turbines can be classified into: static, between rotating parts, and dynamic. Specific sealing areas will be addressed in the following charts.

Sealing Locations

Static:

- Seam / air pipe joints
- Transition mouth
- Between large mating parts (Stein seals used for many years)

Between adjacent rotating parts:

- Joints in rotor cooling system circuits

Dynamic:

- Air sealing locations where labyrinth seals are normally used
- Rotor cooling system inlet and exit
- Shrouded and unshrouded turbine blade tips

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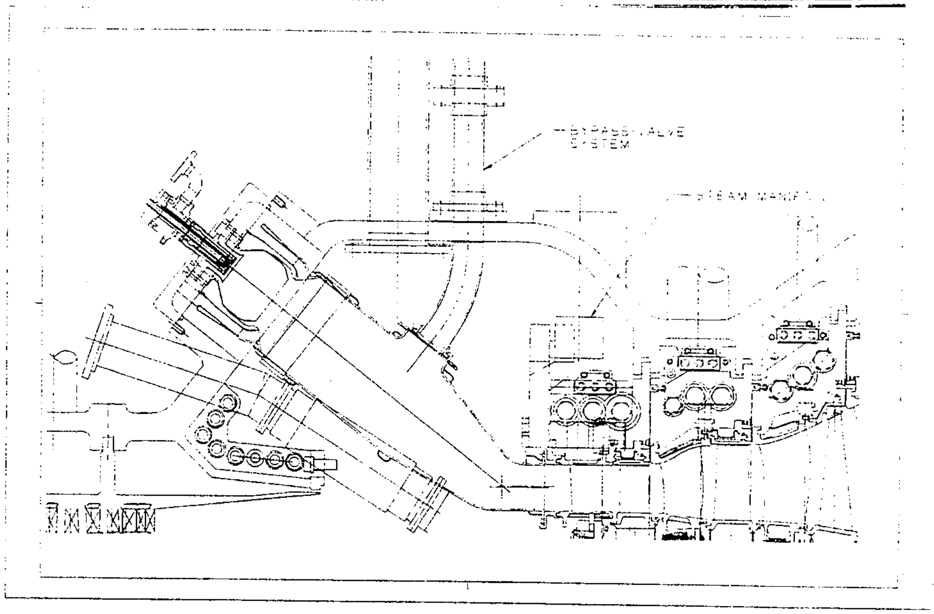
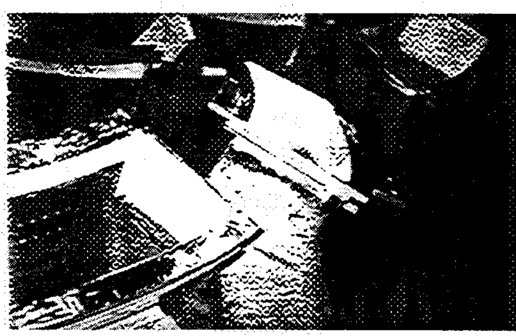
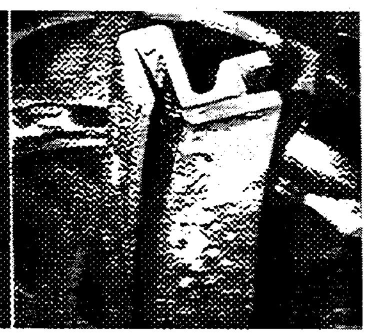
Transition Mouth Sealing







ATS Phase 2 & 3 Technical Review -- Advanced Air Sealing

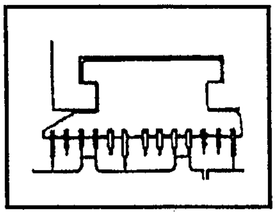
An example of sealing at a static location is sealing around the exit mouth of combustor transition liners. Leakage at this location is beneficial for cooling adjacent parts, but significantly increases emissions. To maintain a required rotor inlet temperature, the combustor maximum temperature must be increased by the dilution effect of leakages at the transition mouth and other locations ahead of the first-stage rotor blades.

The lower two photographs above show how sealing is affected in current hardware. There are several can combustors in each engine. On the sides of the transition mouths (see left photo), there are labyrinth seal teeth which engage as adjacent transitions move together as they heat up. On the top and bottom, connecting metal parts (see right photo) form a seal between the transition mouth and the first-stage vane end walls. The transitions and connecting parts are made of heavy metal because of the hostile environment at this location. Also, these parts are robust to allow rugged handling. Some or all of the combustors are periodically removed for combustor and turbine hardware inspections and replacements.

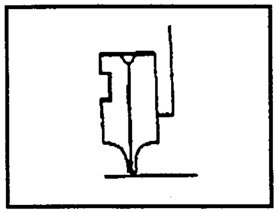
Challenges in decreasing leakage flows are the: need for robust sealing components, high temperature of gases circulating downstream of the seal, and need to provide cooling of adjacent hardware cooled by the higher leakage flows in current engines.

A separate ATS development task has been launched to address improved sealing in this area while meeting the other design constraints.

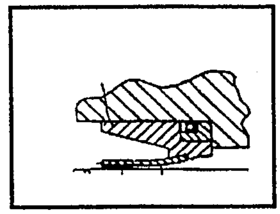
Types of Dynamic Seals



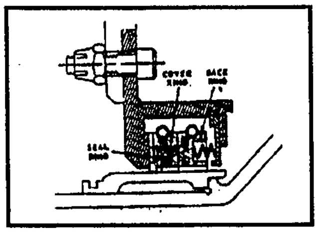
Labyrinth



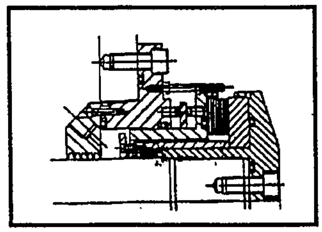
Brush



Compliant



Circumferential



Face

Various types of dynamic seals are being considered for the ATS engine. Prime types are labyrinth seals, brush seals to replace key labyrinth seals, and a face seal at the rear of the turbine rotor. The latter is being considered to meet tight sealing requirements of the closed-loop rotor cooling air system. Cooled compressor discharge air (shell air) enters the rotor rear, flows through between rotor disks and through the turbine blades to provide cooling. The air is returned to the combustor shell to complete the closed loop. A face seal provides very tight sealing at this small diameter location at the rotor rear.

There are four distinct ATS sealing development tasks being pursued. Each addresses engine locations where leakage has a significant impact on performance or emissions.

ATS Sealing Transitioning / Development Programs

- Advanced air seals (brush seals)
- Rotor cooling sealing, especially inlet and exit
- Abradable blade tip seals
- Static sealing (transition mouth, pipe joints, etc.)

These programs transition and extend technology developed for aero engines and other turbomachinery applications to meet large gas turbine engine requirements.

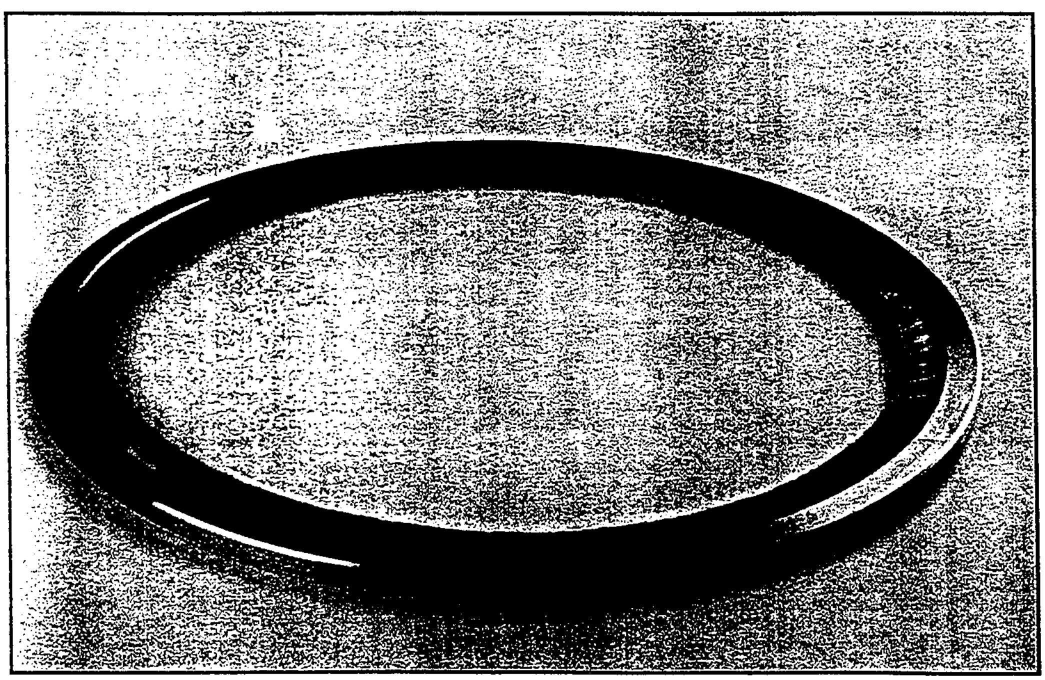
ATS Advanced Air Sealing Program

- Primary focus is brush seals
- Described in two recent AIAA papers:
  - Paper No. AIAA 95-3146, "Brush Seal Development for Large Industrial Gas Turbines," July, 1995
  - Paper No. AIAA 96-3306, Update on Brush Seal Development for Large Industrial Gas Turbines." July, 1996
- Launched after successful preliminary effort at Cross Manufacturing
- Approach:
  - Select candidate seal locations based on benefit trades, risks, etc.
  - Conduct focused transitioning / development efforts for selected locations
  - Validate in a service engine
- Chose EG&G for focused efforts (because of their aero engine brush seal development funded by the USAF and internally, and manufacturing capability)

A major ATS task is to develop advanced air seals to replace or complement labyrinth seals. The task has focused primarily on brush seals. A brief description and current status of this task will be given in the following charts.

Most people who see these charts are aware of what a brush seal is. For reference, a typical brush seal for an aero engine application is shown.

EG&G Brush Seal for Aero-Engine Application



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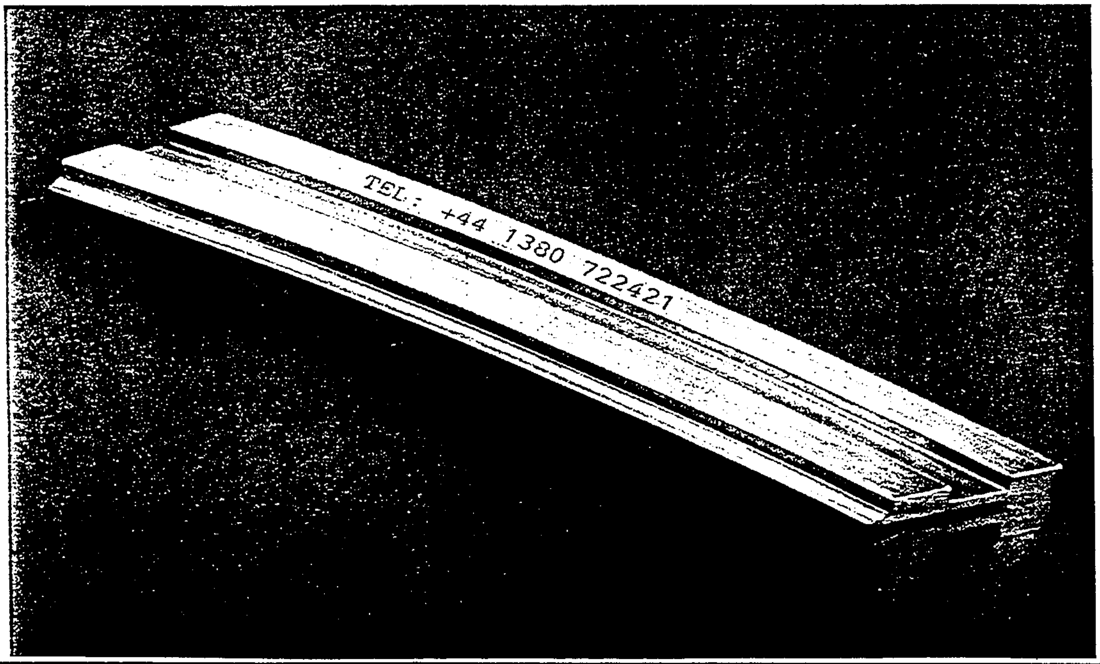
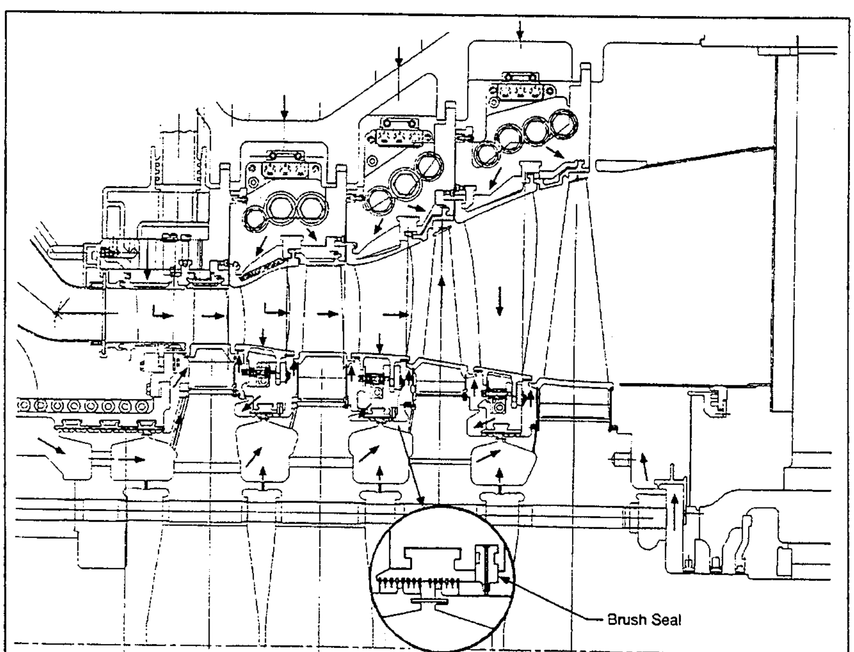
Sample Industrial Brush Seal Segment from Cross



A sample brush seal segment from Cross Manufacturing, Devizes England, has a more rugged construction and is segmented to accommodate large industrial gas turbine requirements.

Such a segmented seal will slide into grooves as shown. To minimize risks, brush seals are being installed in series with labyrinth seals until brush seals are validated for these applications.

501G Turbine Cooling / Leakage Flows



EG&G Development Efforts

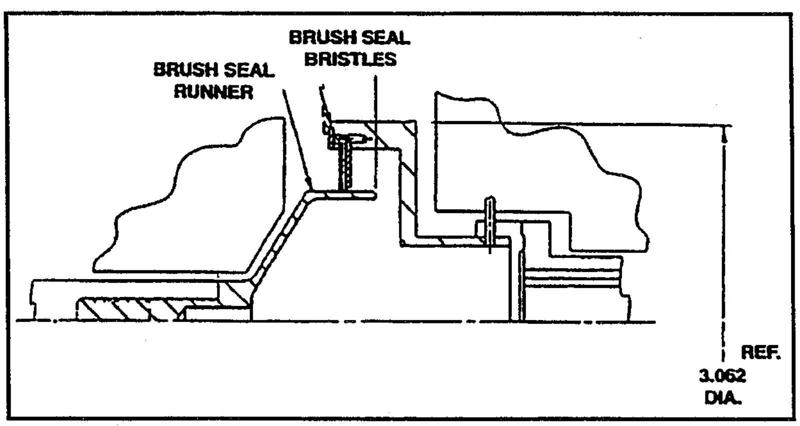
- Challenges:
  - Running against uncoated rotor
  - Design optimization with large radial closures
- Subtasks (for each engine location):
  1) Tribological study -- various bristle alloys run against rotor materials
  2) Seal design
  3) Subscale rig testing of selected configurations
- **First selected engine location -- turbine interstage**

EG&G Sealol was chosen to support Westinghouse in developing brush seals. EG&G has the experience and resources to carry out this effort. The overall program was laid out with a set of subtasks to be performed for each selected engine location. The turbine interstage was selected as the first location to develop brush seals because of the potential performance impact.

Initial tribological testing was performed under simulated seal operating conditions. It screened bristle materials running against uncoated rotor materials and indicated an expected seal life.

Brush Seal Tribology Testing

- Accelerated testing using high-speed rotating rig
- Miniature brush seals tested without air flow
- Temperature, speed, materials, surface conditions, contact pressure modeled
- Matrix of bristle alloys and rotor materials / surface conditions tested
- Torque and temperature histories and hardware inspections used to rank bristle materials for various rotor surfaces



EG&G rig used in tribological testing

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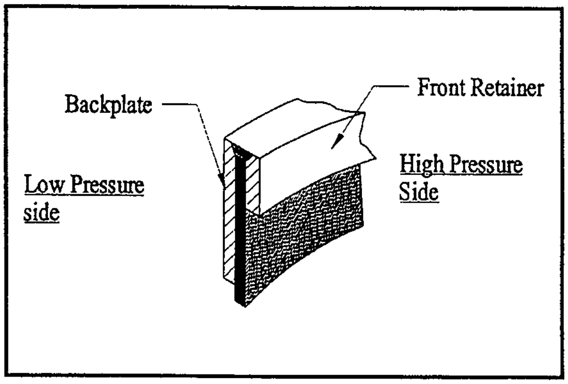
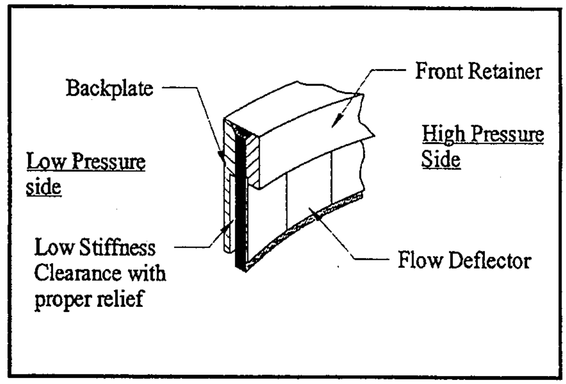
Seal Designs Tested for Turbine Interstage





Standard Seal Design

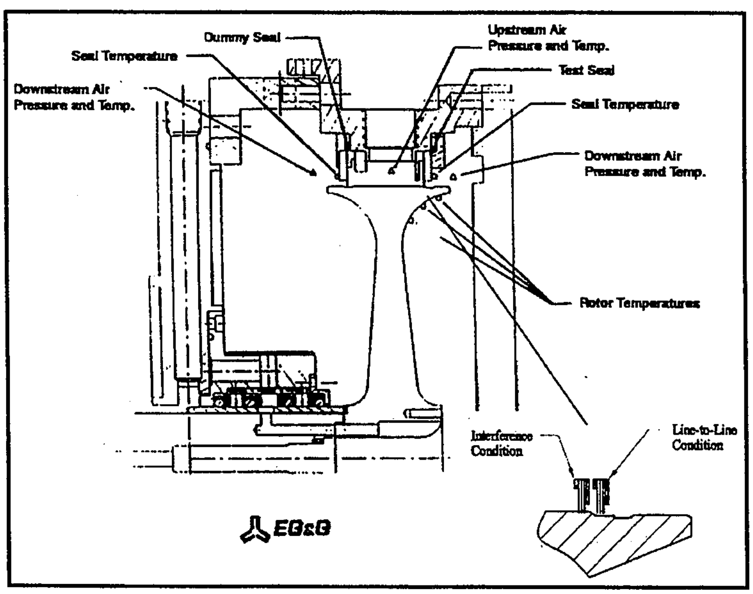
EG&G Advanced Seal Design

Two brush seal configurations have been considered. One has a standard, generic design similar to brush seals produced by several manufacturers. The other has advanced features developed by EG&G. These features address seal hysteresis and bristle wear.

Candidate brush seal were evaluated for wear and performance characteristics in EG&G's Aerospace Rig. The seals were subscale, but the engine pressure drop and rotor speed variations and temperature level were modeled. Seal closure was simulated by moving the seal axially between shallow steps in the rotor surface.

Brush Seal Subscale Rig Testing

- High-speed / temp. "Aerospace Rig"
- Candidate seals from design / tribology subtasks
- Two 1/4 - scale seals tested: a generic and a proprietary seal
- Borescope viewing of bristle movement
- Engine conditions modeled
- Closure cycle simulated via. tapered rotor/varying speed
- Steady-state leakage assessed periodically
- Results used to establish engine seal designs



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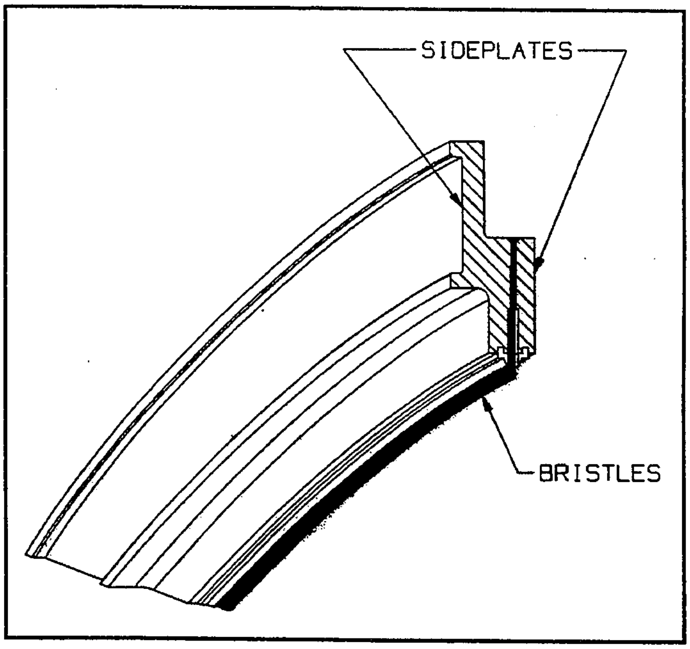
Industrial Brush Seal Segment Being Manufactured by EG&G



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Shown (above) is a sketch of a full-scale brush seal being manufactured for an industrial gas turbine. It has durability and locating features and a shape unique to the sealing location.

In summary, advanced sealing components in the ATS combustion turbine are making significant contributions toward the overall ATS power plant goals. Advanced sealing development tasks are proceeding well and resulting seal components will be validated in the first ATS engine.

Summary

- Decreasing leakages in industrial gas turbines has significant payoffs in improved plant performance
- Large industrial gas turbines offer different seal design constraints/ issues than aero engines
- Advanced air sealing program proceeding well with full-scale seals being manufactured
- Other seal transitioning / development tasks also on track
- Instrumented prototype engine will provide validation of the various advanced sealing features

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